Arcing of Electrical Contacts in Telephone Switching Circuits

Part II—Characteristics of the Short Arc

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(Manuscript received May 27, 1953)

Results are presented of an experimental study of the characteristics of the short arc in air which is the major cause of contact erosion in telephone switching circuits. Measurements were made of the arc initiation voltage, the voltage drop across the arc and the minimum arcing current. The following are the main conclusions: (1) For "normal" contacts in air, the arc is initiated at a constant field strength of a few million volts/cm up to separations of about 2–3 mean free paths of an electron in air. At larger separations the arc is initiated at the well known spark breakdown potentials of air. In vacuum the linear relation holds for larger separations followed by a transition into a square root relation $V_{ai} = K(d)^{1/2}$. *(2) For "clean" contacts in air, no constant field strength line is obtained for separations as low as 1600Å. Instead, the arc is initiated at the spark breakdown potentials of air, possibly due to adsorbed air molecules or due to breakdown along a longer path at the Paschen's minimum potential. In vacuum, it is speculated that the above square root relation will hold. (3) For "activated" contacts and small separations the arc is initiated at a constant field strength of about* 0.6×10^6 *volts/cm. (4) For "normal" contacts the minimum arcing current increases with an increase in the maximum current during the arc due to surface contaminations and the arc cleaning action. (5) For arc currents above 1.5 ampere and energies of the order of thousands of ergs the cathode determines the arc characteristics.*

INTRODUCTION

The electrical erosion of contacts presents an important problem in the design of telephone switching apparatus. There are several physical phenomena that occur between contacts and contribute to their erosion. The short arc,* which may occur on both make and break of a contact,

* The short arc is characterized by its constant voltage, independent of the current, which is of the order of the ionizing potential of the contact material.

is generally considered to be the major contributor. For illustration, a palladium contact, 10^{-4} cm^3 in volume, will last for more than 10^9 operations* only if the arc energy per operation is less than 2.5 ergs. This is based on an erosion rate of 4×10^{-14} cm^3 per erg.[1] Furthermore, a short arc with a half ampere current, lasting for only one microsecond, will dissipate as much energy as 70 ergs. Contact erosion may also take place, though at much lower rates for the usual ranges of current and voltage in switching circuits, due to molten bridges[2] on contact break and due to glow discharge.[3]

In Part I of this series,[4] was discussed the mechanism of the initiation of the short arc as determined by contact and circuit conditions. Three characteristics of the arc were used in the presentation without elaboration as to their nature: (1) the arc initiation voltage, (2) the voltage drop across the arc, and (3) the arc initiation and the arc termination currents. These characteristics have been the subject of a recent study to which this part of the series is mainly devoted.

In the course of this study, it was found that there should be some repetition of previous work to isolate effects of certain pertinent parameters that were not previously given due consideration.

No attempt is made here to give a complete survey of the related studies in the literature. Only a few publications are referred to as typical references to the subjects discussed.

NOTATION

C Capacitance

E_a Energy dissipated in the arc

F Gross field strength between the contacts: $\frac{V}{d}$

I Current

I_i Arc initiation current

I_{max} Maximum current in the arc

I_m Minimum arcing current or arc termination current

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* This is the actual life requirement of some contacts in existing switching circuits.

[1] L. H. Germer and F. E. Haworth, Erosion of Electrical Contacts on Make, J. App. Phys. **20**, p. 1085, 1949.

[2] See for example: J. J. Lander and L. H. Germer, The Bridge Erosion of Electrical Contacts, J. App. Phys. **19**, p. 910, 1948.

[3] F. E. Haworth, Electrode Reactions in Glow Discharge, J. App. Phys. **22**, p. 606, 1951.

[4] M. M. Atalla, "Arching of Electrical Contacts in Telephone Switching Circuits. Part I—Theory of the Initiation of the Short Arc," B.S.T.J., **32**, pp. 1231–1244, Sept., 1953.

K Constant in the relation $V_{ai} = K(d)^{1/2}$
R Resistance
V Voltage
V_{ai} Arc initiation voltage
d Minimum separation between contacts
h Height of a metal bridge formed during one arc
t Time
t_a Arc duration
v Constant voltage drop across the short arc

ARC INITIATION VOLTAGE

Consider the simple contact circuit in Fig. 1 comprising a pair of contacts in series with a resistor R and a variable voltage power supply. By fixing the separation between the contacts and gradually increasing the

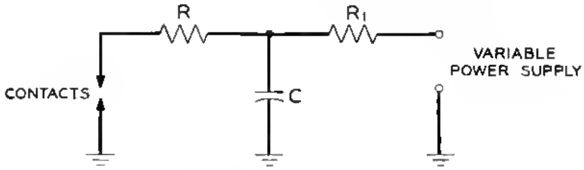

Fig. 1 — Contact Circuit.

voltage, an arc is usually initiated when the voltage reaches a certain value "V_{ai}" called tbe arc initiation voltage. In general V_{ai} is a function of: (1) separation between the contacts, (2) geometry of the contact surfaces, (3) the surrounding atmosphere, and (4) contact material and its surface.

Our experiments were limited to contacts in atmospheric air with special emphasis on separations of the order of and less than the mean free path of an electron in air. For larger separations the arc initiation voltage follows the well known curve of the sparking potential of air.[5] For the smaller separations where the presence of air molecules would not be expected to affect the arc initiation voltage, it was previously reported that breakdowns occurred at some constant field between 0.6×10^6 and 16×10^6 volts/cm.[1, 6, 7]

In our experiments a cantilever bar, described by Pearson,[6] was used. The setting for zero separation was determined by a 0.1 volt source, a

[5] See for instance J. D. Cobine, Gaseous Conductors, McGraw-Hill, N. Y., p. 162, 1941.
[6] G. L. Pearson, Phys. Rev. **56**, p. 471, 1939.
[7] L. H. Germer and J. L. Smith, J. App. Phys. **23**, p. 553, 1952.

10,000 ohms resistor and a cathode relay oscilloscope. The zero setting could be repeated with a precision of ± 500Å. All the reported results were obtained by fixing the contact separation, raising the voltage and observing the breakdown on a cathode ray oscilloscope. Contacts tested were given one of three different surface treatments:

(1) The contact surface was polished with fine emery paper, washed with methyl alcohol, then exposed to the laboratory atmosphere for a few hours. After about 5 arc discharges, readings of arc initiation voltage seemed to vary at random. Contacts thus treated are referred to as "normal" contacts.

(2) Contacts were subjected to arcing for about 5 minutes at the rate of 15 arcs per second. Arcing was produced by the discharge of a half microfarad condenser at 500 volts through a 10-ohm resistor. Measurements of the arc initiation voltage followed *immediately after* this treatment. These contacts are referred to as "clean" contacts. Their behaviour usually changed to that of "normal" contacts after a short exposure to the laboratory atmosphere.

(3) Contacts were subjected to arcing at the rate of 3 arcs per second for about one hour in air saturated with d-limonene. The arc was produced by discharging a 0.1-microfarad condenser at 50 volts through a 100-ohm resistor. These contacts are referred to as "activated" contacts.[8]

Fig. 2 shows the results obtained with "normal" palladium contacts. Each point represents the average of five readings. The maximum spread was 40 per cent of the average. For separations less than 10,000Å, about two mean free paths of an electron in air at normal conditions, a constant gross field strength line of 3×10^6 volts/cm was obtained. At larger separations the measured arc initiation voltages were essentially the well known sparking potentials of air. Fig. 3 shows the corresponding results obtained with "normal" carbon contacts in air. Below a separation of 15,000Å, the arc was initiated at a constant gross field strength of 2.4×10^6 volts/cm. The maximum spread of the individual points was only 15 per cent of the average.

In the absence of air, it is expected that the constant field strength lines will hold for higher separations.* In Table I, Column 2 are given the measured values of the gross field strengths at which the arc was initiated for a group of "normal" contact materials.

* Recent unpublished measurements by Dr. P. Kisliuk on similar contacts in vacuum have indicated that the constant field strength relation $V_{ai} = F(d)$ holds initially for larger separations and is followed by a gradual transition into a square root relation $V_{ai} = K(d)^{1/2}$ as proposed by Cranberg.[9]

[8] L. H. Germer, Arching at Electrical Contacts on Closure—Part I, J. Appl. Phys. **22**, p. 955, 1951.

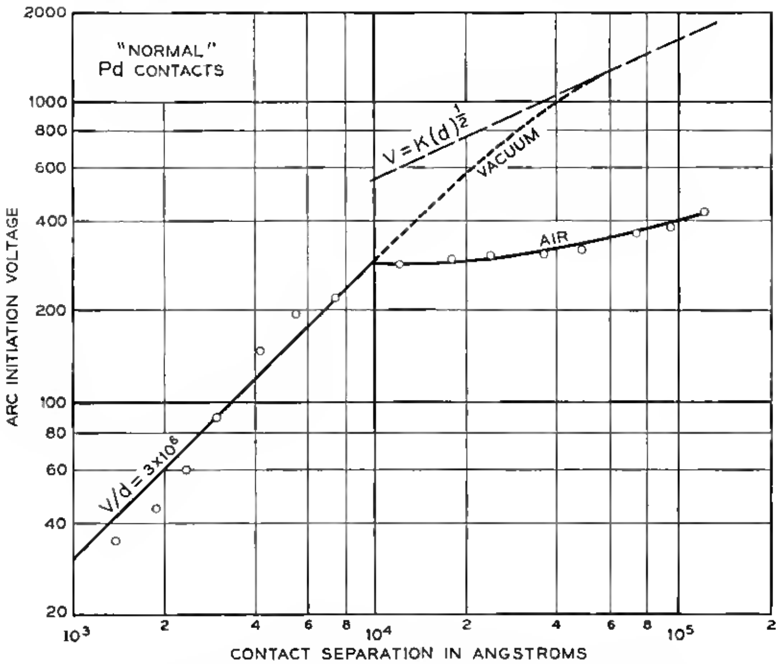

Fig. 2 — Arc initiation voltages for "Normal" palladium contacts.

Due to the spread of the above measurements and their observed dependence on surface exposure and treatment it was suspected that the constant field strength characteristic obtained was due to surface contamination. This was verified by testing contacts cleaned by the heavy arcing process explained above. The results are shown in Fig. 4. The familiar constant field strength line *was not* obtained for separations as low as 1500Å. Instead, the arc was initiated at voltages comparable to the sparking potentials of air. Since the separations were too small, the smallest being three times less than the mean free path of an electron in air, it was thought that the effect was due to some mechanism involving the adsorbed air molecules or due to breakdown along a longer path at the Paschen's minimum potential.[5] In the absence of air, it is, therefore, expected that higher voltages and higher field strengths in excess of 20×10^6 volts/cm, as obtained at 1500Å, will be needed to initiate the arc. It is possible that Cranberg's relationk[9] $V = K(d)^{1/2}$, will hold for separations as low as a few thousand angstroms. In Fig. 4, this relation, with $K = 10^5$ volt. cm$^{-1/2}$, is plotted.

[9] L. Cranberg, The Initiation of Electrical Breakdowns in Vacuum, J. Appl. Phys. **23**, p. 518, 1952.

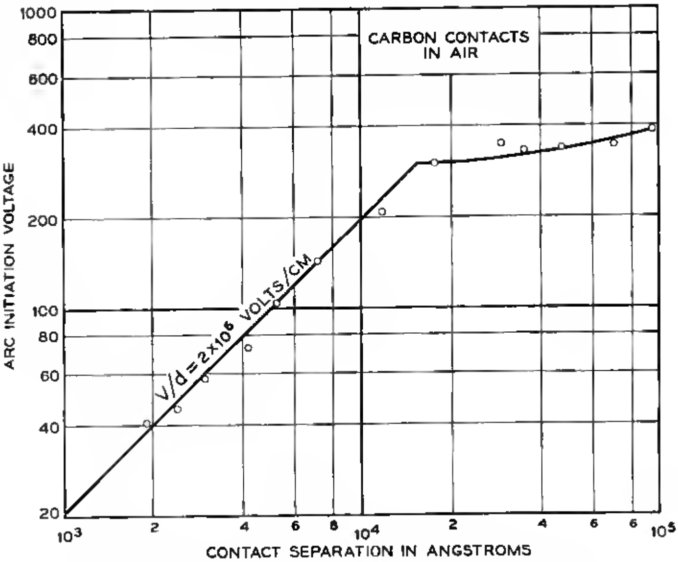

Fig. 3 — Arc initiation voltages for carbon contacts.

For contacts activated in organic vapors, constant field strength lines were obtained. In Fig. 5 results are shown for palladium contacts activated by d-limonene. The average field strength for arc initiation is only 0.6×10^6 volts/cm with a spread of as much as 100 per cent of the average. At separations greater than 50,000Å the arc was initiated by the familiar spark breakdown of air. In vacuum the constant field strength line should hold for larger separations possibly until it intersects Cranberg's line.[9]

Breakdowns at low fields were also observed for metals with inorganic films. For instance Gleichauf[10] obtained a constant field strength line of 0.24×10^6 volts/cm for copper electrodes in vacuum at separations of the order of millimeters. Our measurements on copper contacts at separations less than 10,000Å have shown breakdowns at fields as low as 0.7×10^6 volts/cm. It is concluded that the presence of organic or inorganic films on a contact usually leads to a reduced gross field strength at which the breakdown will occur. The reduction can be by as much as two orders of magnitude. It is possible that this reduction was only apparent and the electrons actually came from the underlying metal by extraction in an intense field set up by the positive ions lying on the surface of the film.[11]

[10] P. H. Gleichauf, Electrical Breakdown Over Insulators in High Vacuum, J. Appl. Phys. **22**, p. 766, 1951.
[11] F. L. Jones, Electrical Discharges in Gases, Nature, **170**, p. 601, 1952.

TABLE I. — ARCING CHARACTERISTICS OF CONTACT MATERIALS

(1) Contact Material	(2) Field strength to initiate the arc for normal contacts. 10^6 Volts/cm.	(3) Short arc Voltage	(4) Minimum arcing current for "clean"* contacts. Amps.
Carbon	2.4	20–43	0.03
Nickel	4.2	12–13	0.4
Palladium	3.0	14–15	1.1
Silver	2.0	11–13	0.8
Tungsten	4.9	12–13	0.7

* For "normal" contacts, the minimum arcing current is less by 50 per cent or more.

The results of the above section are summarized in Fig. 6. The solid lines were actually measured for palladium contacts under different surface conditions. The broken lines are only speculative. For a certain separation and surface condition the arc will be initiated at a voltage as given by the lowest corresponding line in the figure.

VOLTAGE DROP ACROSS A SHORT ARC

The short arc may be defined as a discharge of electricity between electrodes with a voltage drop of the order of the minimum ionizing potential of the atoms of the electrodes.* Furthermore, due to the small separation between the contacts and the local high pressure metal vapor, the characteristics of the established arc are independent of a surrounding atmosphere at normal or low pressures. The short arc is characterized by its constant voltage for currents above a minimum value called the minimum arcing current of the contact. In contrast to the short arc, the long arc between contacts at a fixed separation has a voltage drop which decreases with an increase in current.[12] *Most arcs occurring between contacts on both make and break of telephone switching circuits, are short arcs.* In Table I, Column 3, are given our measured values of the short arc voltage for a few materials.

ARC INITIATION AND TERMINATION CURRENTS

The arc termination current or minimum arcing current is defined as the lowest current at which the arc can be sustained. The arc is extin-

* The arc voltage is about 50 per cent higher except for the carbon arc which has a much higher voltage; see Table I, Column 3.

[12] See for instance: K. Gaulrapp, Untersuchung der elaktrischen Eigenschaften des Abreisbogens, Ann. Physik. **25**, p. 705, 1936.

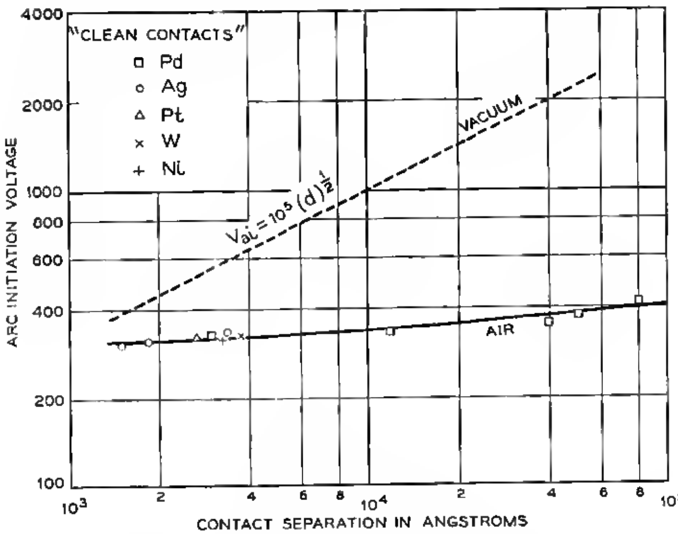

Fig. 4 — Arc initiation voltages for "Clean" metals.

guished when the circuit current drops to this value. To initiate the arc a minimum current must be furnished by the circuit called the arc initiation current. It was previously shown[4] that the arc initiation and termination currents are essentially the same numerically. The existence of these limiting currents as such, rather than current densities, is not understood from a fundamental standpoint.

The limiting currents are a function of the contact material and are appreciably affected by the surface condition of the contacts. Surface contaminations generally reduce the limiting currents of the contacts. The results presented here were obtained by measuring the residual voltage in an R-C circuit following an arc. This voltage is equal to $I_m R$, from which I_m was determined. Our measurements are given in Table I, Column 4 for "clean" contacts. The maximum spread is 20 per cent of the average. For normal contacts, however, surface contamination causes a wide variation in the results. Furthermore, the maximum intensity of the arc, or the maximum current furnished by the measuring circuit, was found to have an appreciable affect on the measurements. This appears to be due to the surface cleaning action of the arc. This effect is demonstrated in Fig. 7 for "normal" palladium contacts. Each point represents an individual measurement of I_m plotted against the corresponding maximum current during the arc. An R-C contact circuit was used. While the measurements show a considerable spread, they indicate a definite trend of an increase in I_m with increasing I_{max}.

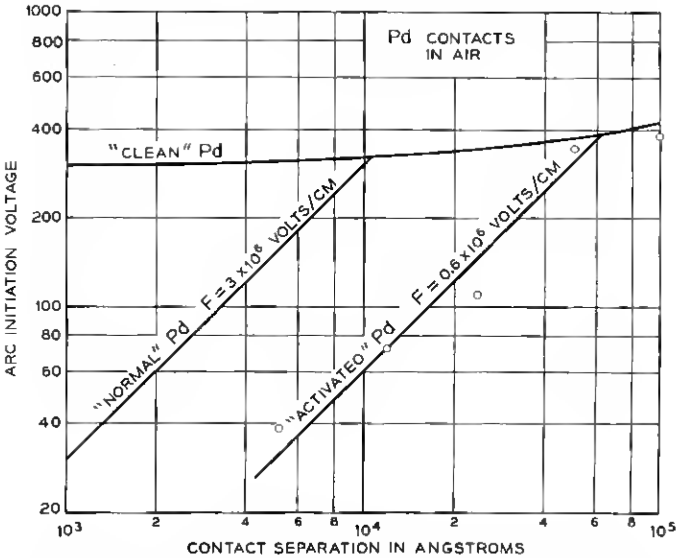

Fig. 5 — Arc initiation voltages for "Activated" palladium contacts.

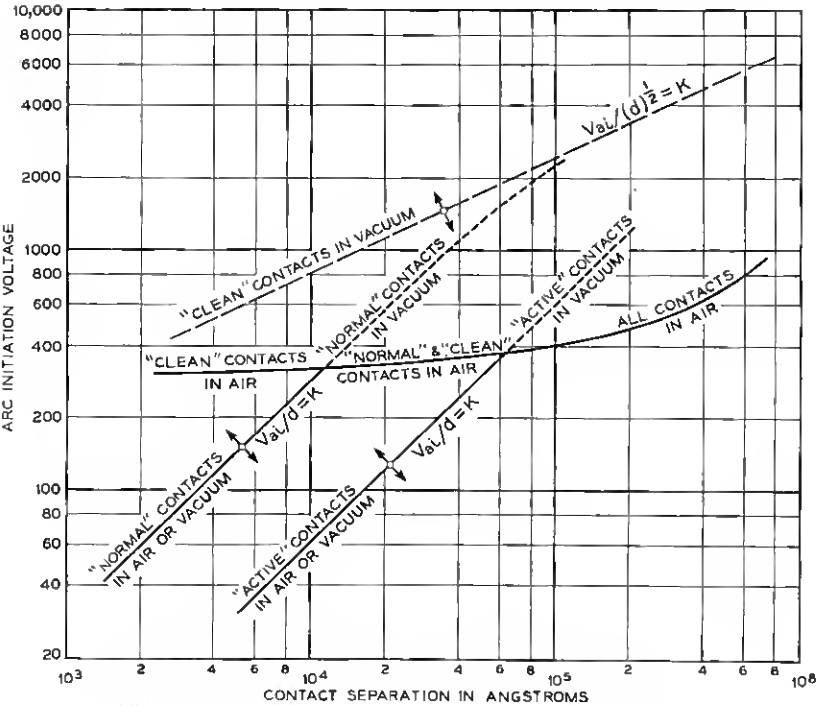

Fig. 6 — Summary of results of arc initiation voltages.

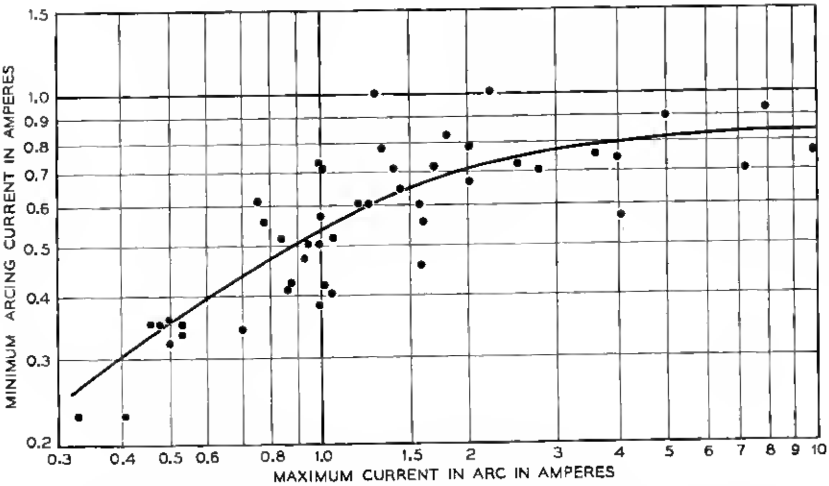

Fig. 7 — Dependence of minimum arcing current on maximum arc current.

In the first part of this paper it was shown that contact activation by organic vapors reduces the arc initiation voltage for a fixed separation. In other words, for a pair of closing contacts the arc will be initiated at a wider separation and a longer arcing time is obtained. In addition, activation tends to decrease the minimum arcing current. Germer[8], measured a minimum arcing current of only 0.027 to 0.037 ampere for active silver. Our measurements for active palladium gave a minimum arcing current of 0.1 ampere. This substantial decrease in the minimum arcing current of contacts due to surface activation usually causes a further increase in the arcing time. Contact activation, therefore, enhances arcing between closing contacts in two ways; first, by initiating the arc at wider separations, and second by maintaining the arc at much smaller currents. The following results are presented to indicate the quantitative significance of contact activation. A pair of "normal" palladium contacts were operated in air saturated with d-limonene at 3 cps. The contacts closed a circuit consisting of a 0.5-microfarad condenser, charged to 50 volts, in series with a 100-ohm resistor. The transient on make was observed on a cathode ray oscilloscope to determine the arcing time. The arc energy E_a was calculated and the ratio $E_a/Cv\ (V_0 - v)$ was plotted against the number of operations, Fig. 8. The denomenator is the maximum arc energy, which is only attained if the arc is maintained until the current reaches zero. The results indicate a rapid increase of the arc energy corresponding to an increase in surface activation. When the contacts become fully active, the arc energy was about two orders of

magnitude greater than the energy for inactive contacts. Contacts may also be activated by inorganic films. Experiments on palladium and silver contacts have shown* that glow discharge between contacts operating in air produced a second type of activation. Nitrides were formed on the contact surfaces and the minimum arcing current dropped to about 0.1 ampere for silver and 0.2 ampere for palladium. This effect was more pronounced with silver contacts.

In carrying out the measurements of the minimum arcing current it was observed that the arc was generally interrupted by one of three causes (1) the minimum arcing current was reached, (2) physical closure of the contacts, and (3) shorting of the arc by a metal bridge formed during the arc. A study of the bridge formation has shown that the height of the bridge was a function of the arc energy. The bridge height was measured by setting the zero separation point before and after the arc. The difference gave the height of the bridge. This was plotted in Fig. 9 against the measured arc energy. The height of the bridge increased roughly with the cubic root of the arc energy up to energies of

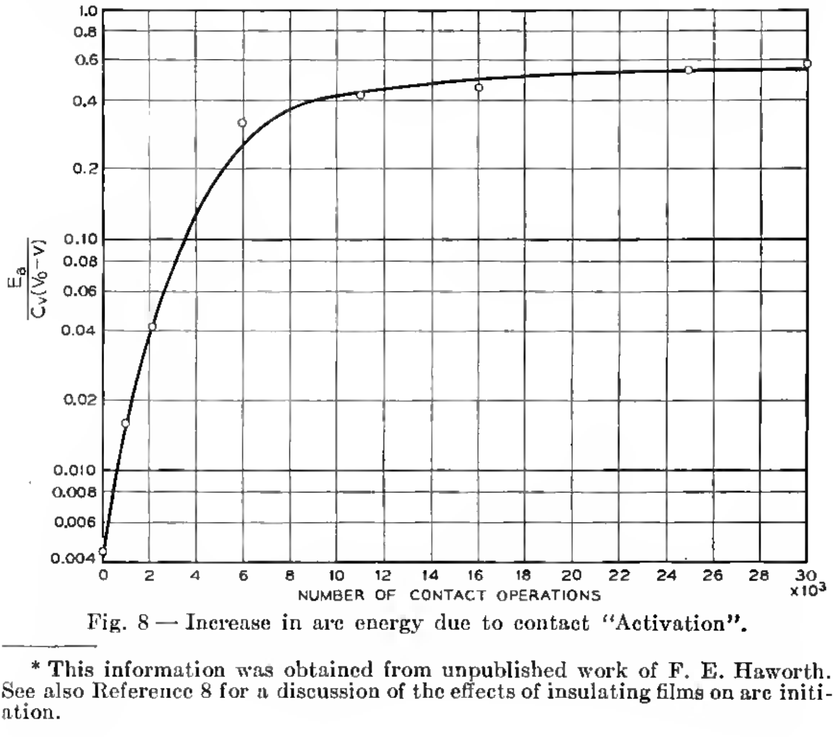

Fig. 8 — Increase in arc energy due to contact "Activation".

* This information was obtained from unpublished work of F. E. Haworth. See also Reference 8 for a discussion of the effects of insulating films on arc initiation.

about 800 ergs. This was followed by a rapid transition into metal *loss* instead of a bridge. This loss increased with increase in energy.

DISSIMILAR CONTACTS — EFFECT OF POLARITY ON ARC CHARACTERISTICS

An experiment was carried out to find the contributions of the anode and cathode in determining the characteristics of the arc. Use was made of the fact that carbon contacts are unique in having low minimum arcing current and high arc voltage compared to most metals; see Table I. Furthermore, carbon contacts always gave a constant field strength line for arc initiation at small separations even when they were cleaned by the heavy arcing process. Tests were carried out with a variety of contact metals against carbon. All the results obtained were qualitatively the same. For illustration only the experiments with palladium-carbon contacts are reported here.

Test specimens were carefully prepared in the following fashion. Palladium to palladium contacts, mounted on the cantilever bar set-up, were cleaned by the heavy arcing process. One contact was removed and replaced by a carbon contact with its surface polished and freed from

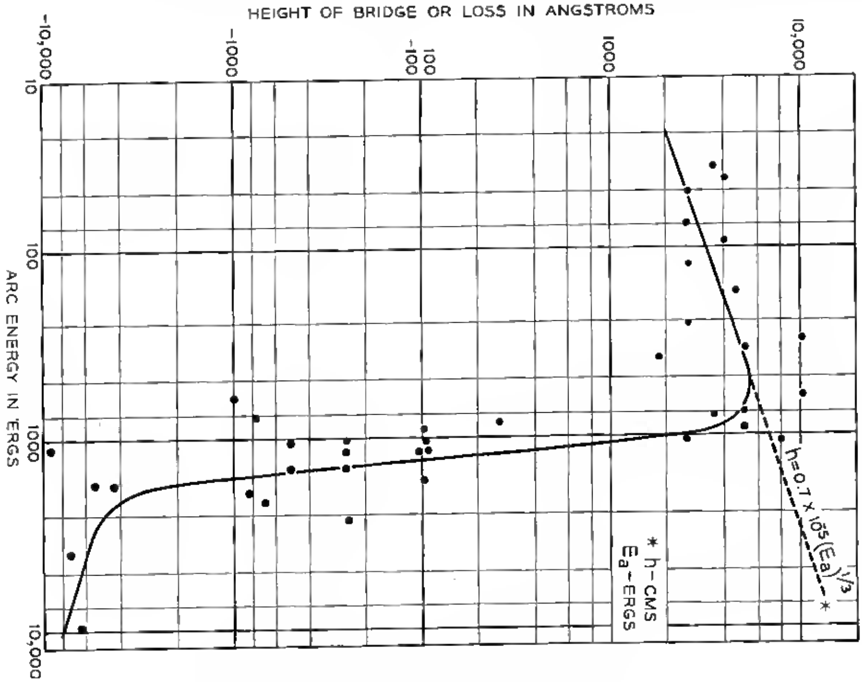

Fig. 9 — Bridge formation during the arc.

TABLE II — EFFECT OF POLARITY ON THE CHARACTERISTICS OF THE ARC — PALLADIUM-CARBON CONTACTS

(1) Contact Configuration	(2) Arc initiation voltage at 6000A separation	(3) Arc voltage v	Minimum arcing current. I_m amps.
C^+, Pd^-	300	13–15	0.2–0.5
Pd^+, Pd^-	320	14–15	1.1
C^-, Pd^+	130	20–30	0.2–0.3
C^-, C^+	120	20–43	0.03

loose particles. The separation between the contacts was set at 6000Å. By gradually raising the voltage across the contacts and observing it on a cathode ray oscilloscope, the arc initiation voltage was determined. The same measurement was repeated several times. Preceding *each* measurement, the contacts were recleaned by the same process explained above. The polarity was then reversed and a new set of measurements was taken. The results are shown in Table II, Column 2. They indicate that the arc initiation voltage is determined by the cathode. This furnishes support to the postulate that field emission is the first step of the mechanism of arc initiation. By recording the voltage across the contacts during the arc, measurements were made of the arc voltage and the minimum arcing current. The results are given in Table II, Columns 3 and 4. The arc voltage measurements indicate rather conclusively that the arc voltage is determined by the cathode. The minimum arcing current measurements, however, were only slightly, yet consistently, higher with a palladium cathode. It is thought that during a single short arc, particularly with the high intensity arcs used, there is a certain amount of exchange of materials between the electrodes. This exchange is possibly responsible for the observed influence of the anode on the arc characteristics.

It is concluded that the arc initiation voltage as well as the arc voltage are characteristics of the cathode while the minimum arcing current seems to be influenced by both electrodes with stronger inclination towards the cathode characteristics.* The following reservation, how-

* Early experiments by H. E. Ives[13] have led to the conclusion that the arc voltage is a characteristic of the *anode*. In his experiments, however, currents of the order of one ampere were established in the circuit while the *contacts were closed*. Arc measurements were made during the subsequent break of the contacts. It is thought, therefore, that metal bridges must have formed during the break, transferring metal from the anode to the cathode.[2] The arc produced must have been influenced accordingly. In our experiments this difficulty was entirely eliminated.

[13] H. E. Ives, Minimal Length Arc Characteristics, J. Franklin Inst. **198**, No. 4, 1924.

ever, has to be made. All these measurements, although made at a voltage range between 50 and 400 volts corresponding to a contact separation range between 1500 and 100,000Å, had high maximum currents above 1.5 amperes. The energy dissipated in each arc was of the order of thousands of ergs. This reservation is made because recent studies of metal transfer have indicated a reversal in the direction of transfer between the anode and the cathode depending on the rate of energy dissipation in the arc.

ACKNOWLEDGEMENTS

I am indebted to L. H. Germer, P. Kisliuk and F. H. Haworth for much valuable discussion and to A. S. Timms for assistance with many of the experiments reported here.